Government of **Western Australia**
Department of **Mines and Petroleum**

RECORD 2009/4

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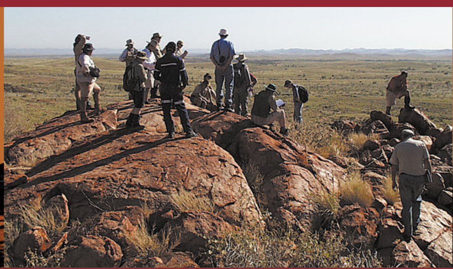
by F Pirajno and RA Burlow

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THE MAGELLAN NON-SULFIDE LEAD DEPOSIT, YERRIDA AND EARAHEEDY BASINS, WESTERN AUSTRALIA

by
F Pirajno and RA Burlow[1]

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Geological Survey of Western Australia

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The Magellan non-sulfide lead deposit, Yerrida and Earaheedy Basins, Western Australia

by
F Pirajno and RA Burlow[1]

Abstract

The stratabound Magellan Pb deposit is located in an outlier of the Paleoproterozoic Earaheedy Group overlying the southeast Yerrida Basin. A feasibility study of the Magellan prospect was completed in 2001, with proven and probable ore reserves of 8.5 Mt grading 7.12% Pb. The deposit is exploited from two open pits; Magellan and Cano. The lead orebodies are hosted in a silicified dolomitic collapse breccia, and underlying altered and weathered sandstone and siltstone.

The host succession comprises, from top to bottom: a lateritic unit overlying a zone of silicified (silcritized) clay-quartz breccia, overlying saprolitic clay breccia and siltstone. The footwall consists of black shales of the Maraloou Formation (Yerrida Basin). Magellan is a non-sulfide mineral system with cerrusite, anglesite, plattnerite, coronadite, pyromorphite, and plumbogummite as ore minerals. The lack of sulfides and the sole presence of oxide minerals suggest that the ore was formed under physico-chemical conditions conducive to the precipitation of Pb carbonate and Pb sulfate. It is proposed that the Magellan lead deposit represents the residue from Mississippi Valley-type (MVT) mineralization hosted in the Sweetwaters Member of the Yelma Formation that underwent prolonged weathering, which led to dissolution, volume reduction, and oxidation of the galena and sphalerite, as well as leaching out of highly mobile Zn, leaving behind the Pb carbonate and sulfate mineralization.

KEYWORDS: Mississippi Valley-type, lead carbonate, stratabound, Earaheedy Basin, Yelma Basin, Earaheedy Group.

Introduction

The <1.84 Ga Earaheedy Basin lies at the eastern end of the Capricorn Orogen and unconformably overlies rocks of the Yilgarn Craton, the Mooloogool and Windplain Groups (Yerrida Basin) and possibly the Bryah Group (Bryah Basin; Fig. 1). Scattered outliers indicate that the basin originally extended much further to the southeast, southwest, and to the north and northeast beneath the later Proterozoic Collier and Officer Basins. Outliers of the basal lithologies of the Earaheedy Basin on the southeast Yerrida Basin, host the Magellan non-sulfide lead mineralization (Fig. 1).

The Earaheedy Basin developed on the trailing northeastern margin of the Yilgarn Craton during the Paleoproterozoic and its geology was described by Bunting (1986), Pirajno et al. (2004), and Pirajno et al. (in press). The Earaheedy Basin contains the Earaheedy Group, a 5-km-thick succession of shallow marine clastic and chemical sedimentary rocks that are unconformable on the Yilgarn Craton and the c. 1.84 Ga Mooloogool Group (Yerrida Basin). The Tooloo Subgroup lies at the base of the Earaheedy Group and consists of the basal Yelma Formation (sandstone and stromatolitic carbonates) overlain successively by the Frere Formation (Lake Superior-type granular iron-formation and shale), and the Windidda Member (iron-rich shale and carbonates). The overlying Miningarra Subgroup, in ascending order, consists of the Chiall Formation (silty and sandy mature clastic units, commonly glauconitic), Wongawol Formation (fine-grained clastic and carbonate rocks), Kulele Limestone, and Mulgarra Sandstone. The ages of detrital zircons from the Yelma and Wongawol Formations indicate sediment provenance from the Archean Yilgarn Craton and from Paleoproterozoic rocks, possibly the Gascoyne Complex (Pirajno et al., 2004). Apart from minor ash-tuff beds in the Frere and Wongawol Formations, no igneous activity is recorded in the basin. The Earaheedy Group is intruded by c. 1.07 Ga mafic sills and dykes of the Warakurna large igneous province (Pirajno et al., 2004; Morris and Pirajno, 2005).

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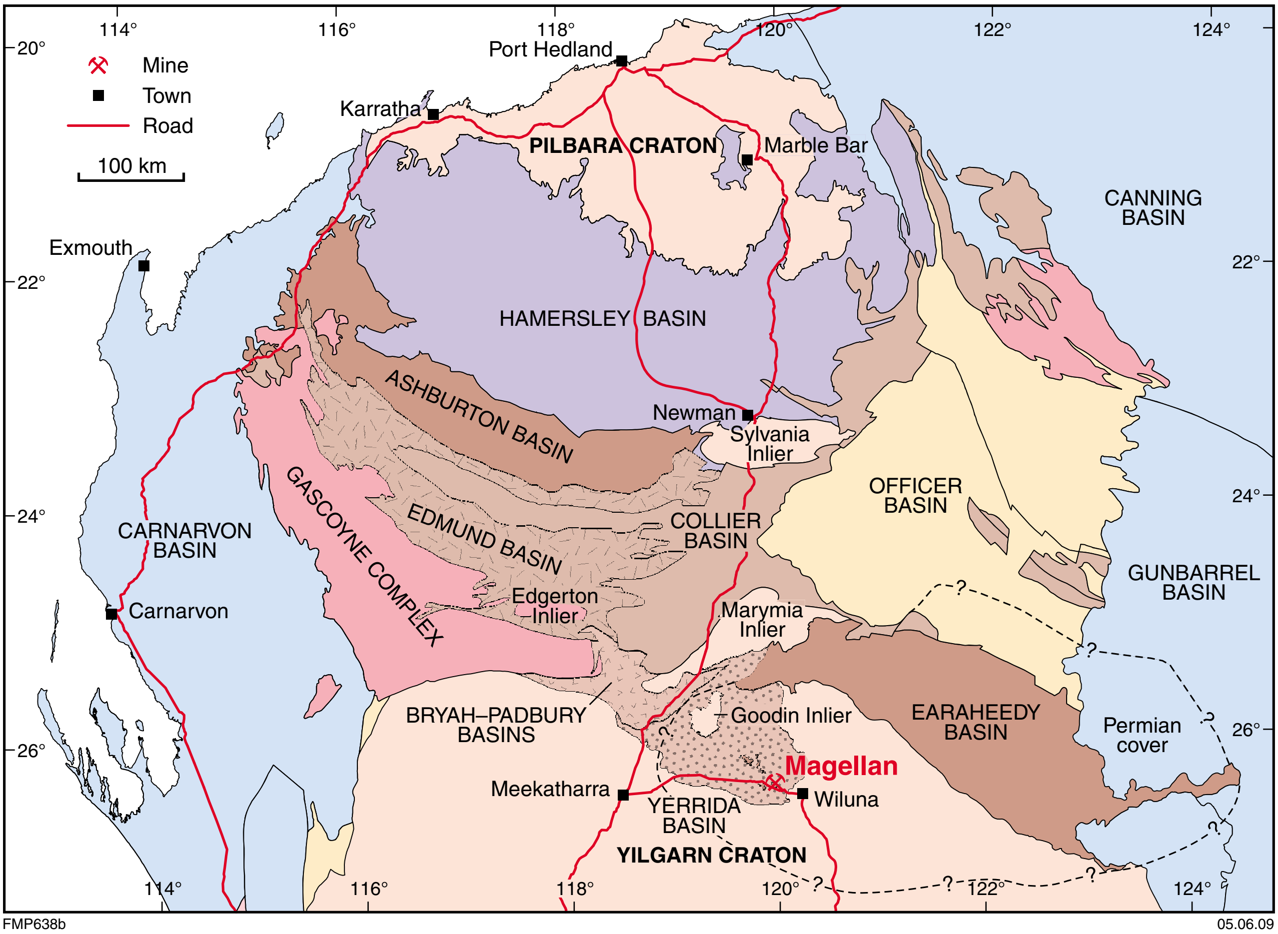

Figure 1. **Tectonic units of the Capricorn Orogen, position of the Yerrida and Earaheedy Basins and the Magellan non-sulfide lead deposit (dashed line indicates possible original extent of Earaheedy Basin).**

The exposed Earaheedy Basin is deformed into an asymmetric east-plunging open syncline, with a vertical to locally overturned northern limb. This regional structure was formed by compressive movements from the northeast, which created a zone of intense deformation along the exposed northern margin of the Earaheedy Basin. This zone of deformation, referred to as the Stanley Fold Belt, is characterized by reverse faults and shear zones that dip steeply to the north. The Stanley Fold Belt was probably the result of a transpressive deformation, and has been related to the 1.79 – 1.76 Ga Yapungku Orogeny (Bagas, 2004), which is thought to record the collision of the northeast Yilgarn Craton with the North Australian Craton (Smithies and Bagas, 1997; Li, 2000). More recently, micas in a sample (GSWA 171772) of quartz–muscovite–chlorite schist from the Stanley Fold Belt, dated using the $^{40}Ar/^{39}Ar$ system (Pirajno et al., in prep), yielded plateau ages of c. 1650 Ma, suggesting a link with deformation associated with the Mangaroon Orogeny (Sheppard et al., 2005). This event may be of particular importance for the development of Mississippi Valley-type (MVT) occurrences in the Earaheedy Basin and consequently for the Magellan deposit, as is explained more fully in the *Genetic model* section.

Within the underlying Yerrida Basin, the Mooloogool Group overlies the Windplain Group and contains the Thaduna, Doolgunna, Killara, and Maraloou Formations (Fig. 2). The contact between the two groups is poorly defined, but where exposed is disconformable. Conglomerates and turbidite facies rocks in the Thaduna and Doolgunna Formations are indicative of a high-energy environment, in contrast to the shallow, stable, low-relief environment of the Windplain Group. The Killara Formation contains tholeiitic lavas and gabbro–dolerite sills, and interfingers with the Maraloou Formation. The Maraloou Formation comprises laminated siltstone, sulfidic and graphitic shale, marl, dolostone, and minor chert and is discussed below.

This Record, reports on the geology and mineralization of the Magellan lead deposit at the base of the Earaheedy Group, overlying the Mooloogool Group. The Magellan deposit is entirely sulfide-free, consisting only of carbonate and oxide lead mineral species, and as such falls in the category of non-sulfide ore systems defined in Hitzman et al. (2003). The Magellan deposit lies in the MEREWETHER 1:100 000 map sheet (Ferdinando and Tetlaw, 2000). Similar mineralization exists in smaller prospects that lie south and southwest of Magellan, mainly along the unconformity surface between the Juderina Formation (Windplain Group) and small outliers of the Earaheedy Group. These include the Canon, Cortez, Drake, and Pizarro prospects that are found west and southwest

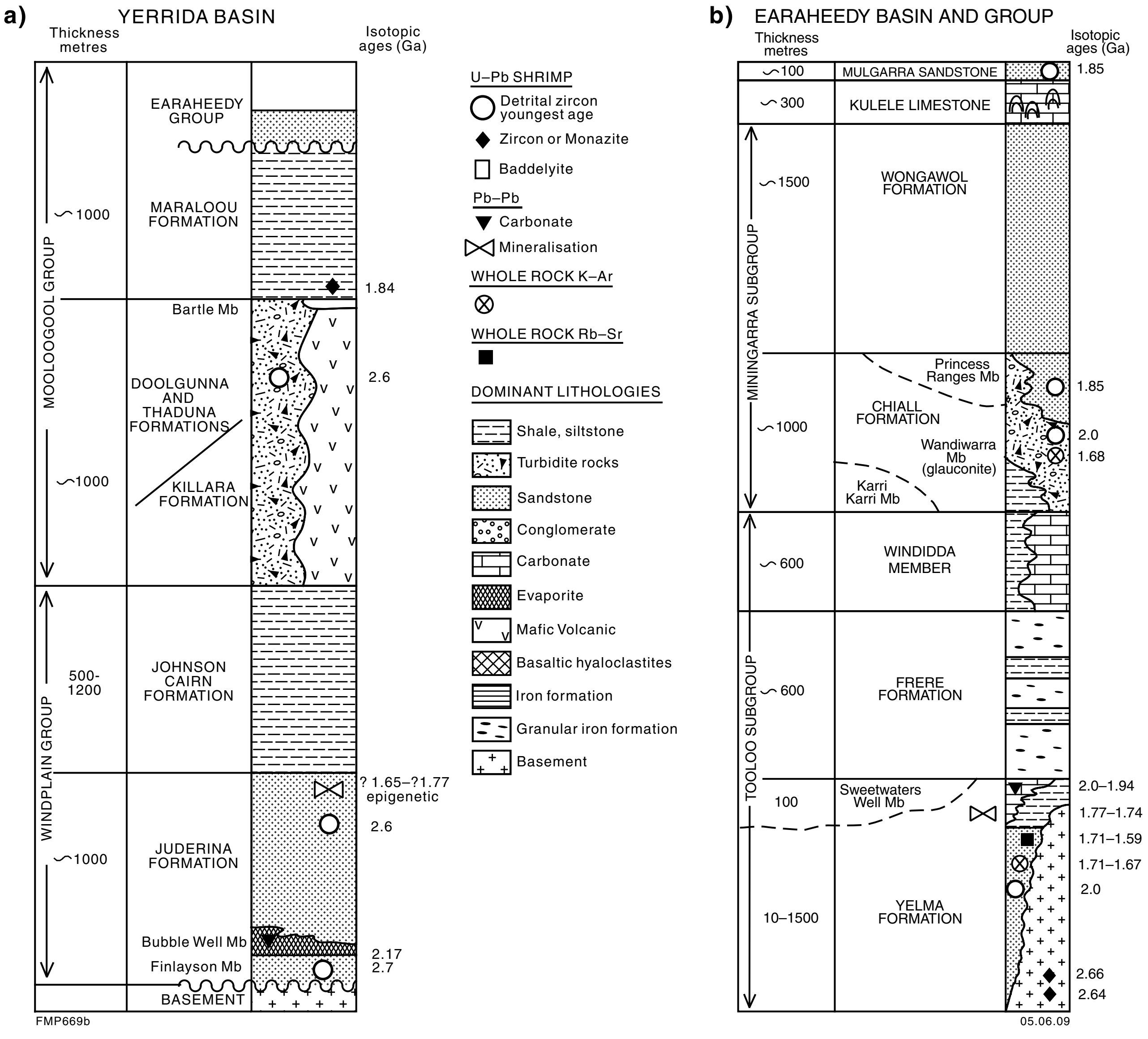

Figure 2. Stratigraphy and geochronology of the Yerrida (a) and Earaheedy (b) Basins. After Pirajno et al. (2004).

from the Magellan deposit. Preliminary accounts of the Magellan mineralization have been published by McQuitty and Pascoe (1998), Pirajno and Adamides (2000), and Pirajno (2004, 2008).

Regional stratigraphy

The stratigraphy of the Earaheedy Basin and that of the older Yerrida Basin (Windplain and Mooloogool Groups) is shown in Figure 2, and discussed in detail by Pirajno et al. (2004 and references therein). Of relevance to this work is the stratigraphy of the Yelma Formation, at the base of the Earaheedy Group, which hosts the Magellan orebodies, and the underlying Maraloou Formation at the top of the Mooloogool Group (Yerrida Basin). A disconformity separates the Maraloou Formation from the overlying Yelma Formation.

Maraloou Formation

The Maraloou Formation is a 1000 m-thick succession of argillaceous sedimentary rocks at the top of the Mooloogool Group in the Yerrida Basin, and is well developed in the southern parts of the Yerrida Basin. It interfingers with mafic volcanic and intrusive rocks of the Killara Formation, which enabled U–Pb SHRIMP dating of monazite from peperite margins that yielded an age of c. 1.84 Ga (Rasmussen and Fletcher, 2002). This age is considered a minimum depositional age for the Maraloou Formation and, by inference, it provides a maximum age limit for the deposition of the overlying Yelma Formation.

The Maraloou Formation consists of sulfidic and graphitic shale, finely laminated siltstone, argillaceous dolomitic limestone, and interbedded siltstone with thin beds of limestone and dolomite. The upper part of the Formation is exposed in a 60 m-section at Mount Russell (MGA 783541E 7066203N), where the disconformity with the overlying Yelma Formation is exposed (Fig. 3). This section consists of massive to flaggy dolostone and argillite beds exhibiting decimetre-scale rhythmic banding and metre-scale wavy banding. The dolostone is commonly pink to purple-brown in colour and flecked with iron and manganese oxides. The lower parts of the formation consist of carbonaceous facies with local bands of marlstone and carbonate nodules up to 50 cm in diameter. Drillcore and drill cuttings show sulfides (predominantly pyrite) that are locally abundant as cubes, framboidal aggregates, and nodules; and bands of carbonaceous and calcareous argillite with carbonate concretions, some with sulfide cores. These features are interpreted as indicative of deposition under anoxic conditions.

On MOOLOOGOOL, the Maraloou Formation (Pirajno et al., 1998) consists of thin-bedded siltstone, carbonaceous shale, and quartz wacke intercalated with basalt and dolerite near the top. The dolomitic units consist of packed aggregates of dolomite euhedra, which show zoning from a dark Fe-rich core to clear dolomite rims. The dolomitic rocks are also variably silicified and chertified. They are intercalated with thin amygdaloidal basalts near the contact with the Killara Formation. Along strike from the dolomite are thinly bedded siltstone and black sulfidic shale, the latter consisting of fine lenticles or laminae of silt-sized quartz grains, sericite, chlorite, kaolinite, Fe oxides, and carbonaceous matter. Pyrite and chalcopyrite are the main sulfides, and are commonly replaced by secondary oxides and oxyhydroxides.

Yelma Formation

The Yelma Formation is described in detail in Pirajno et al. (in press) and the following is summarized from this work. The Yelma Formation is the basal unit of the Earaheedy Group and comprises a marine transgressive succession of sandstone, shale, carbonate, and minor siltstone and conglomerate. Braided fluvial facies are preserved in places at the base of the Formation. A 100 m-thick stromatolitic carbonate facies in the southwest of the basin is differentiated as the Sweetwaters Well Member. MVT stratabound sulfide mineralization is present at various localities in this Member (Fig. 4), which is variably altered to chert, due to surface weathering.

The thickness of the Yelma Formation ranges from 3 m in the southeast to a maximum of 1500 m in the Stanley Fold Belt, although it is possible that the increased thickness in the fold belt may be caused by structural repetition. In the westernmost parts of the Earaheedy Basin, the Yelma Formation is a unit of clastic and dolomitic sedimentary rocks at the base of the Earaheedy Group. In this area the base of the Yelma Formation includes quartz lithic sandstone and quartz conglomerate, which lie unconformably on quartz arenite of the Finlayson Member of the Juderina Formation (Fig. 2). This is exposed 1.5 km east of Freshwater Well (MGA 79936E 7156452N), on the

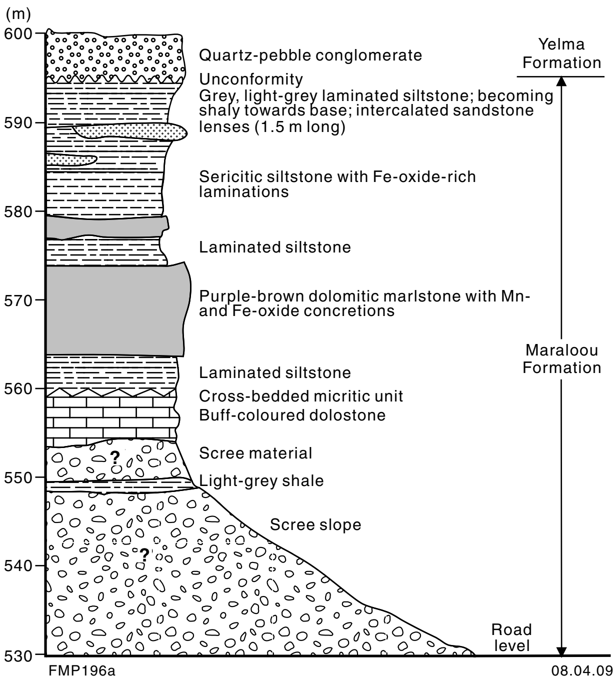

Figure 3. Measured stratigraphic section at Mount Russell (width of column reflects relative resistance to weathering); after Pirajno and Adamides (2000).

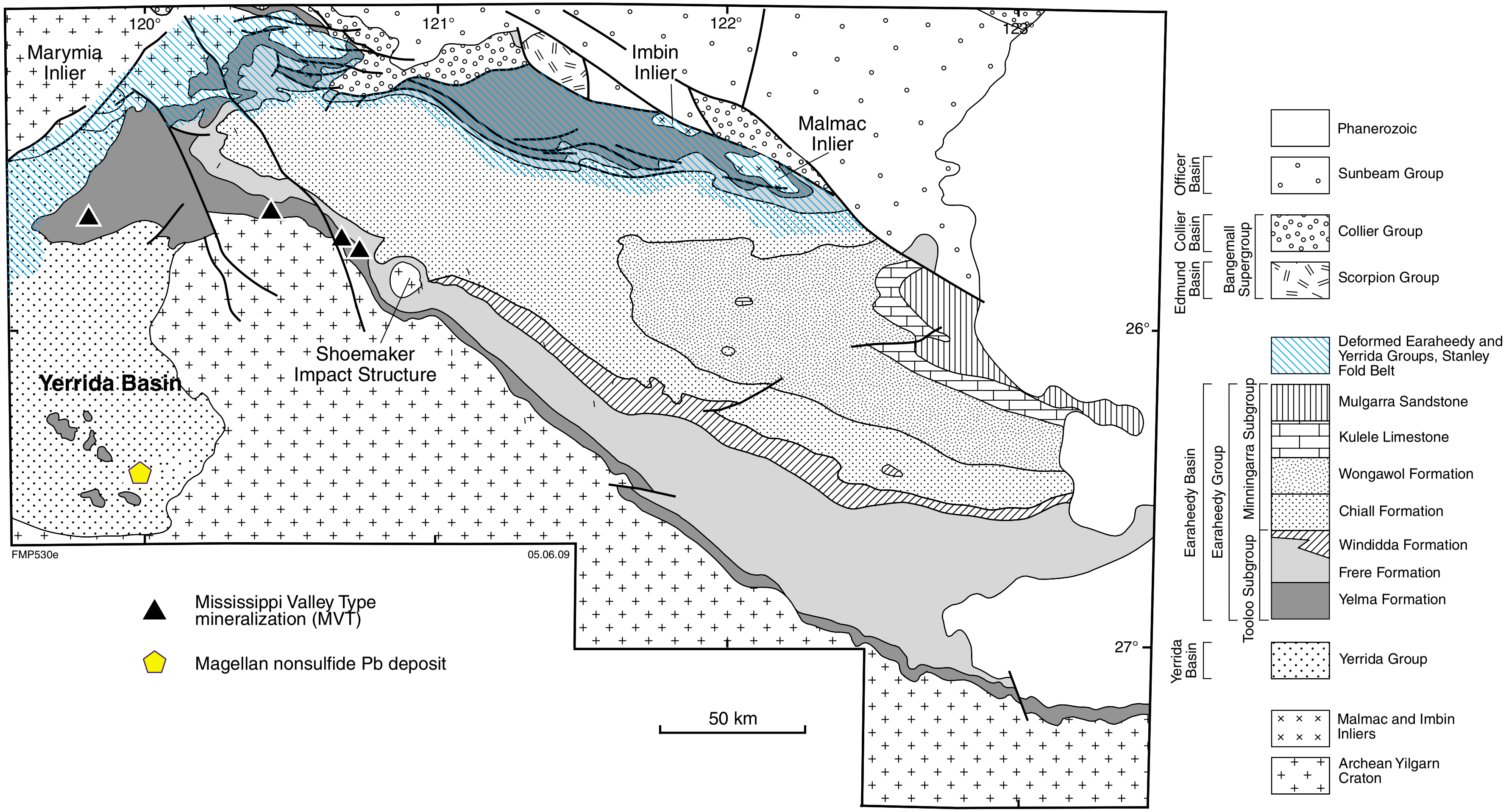

Figure 4. Simplified geology of the Earaheedy Basin, position of Magellan non-sulfide lead deposit and distribution of MVT mineral occurrences; after Pirajno (2004).

southern edge of Lake Gregory. The main constituents of the lithic sandstone, near the base of the Yelma Formation, are quartzose and sericitized lithic grains, and subordinate polycrystalline quartz, chlorite, and turbid feldspar.

Two boreholes drilled 3 km south of Little Well (CTW001 and CTW002, MGA 76036E 7167520N; Meakins and Watsham, 1994), together with field observations, enable a representative 400 m-thick stratigraphic section of the Yelma Formation to be constructed. This section, schematically represented in Figure 5, consists of grey to pink, massive, silicified dolomite and argillaceous interbeds in the lower 150 m. This interval is overlain by a 120 m-thick unit of dolomite with solution breccia interbeds containing some interstitial kerogen material and sulfides. This is in turn overlain by about 100 m of pink to grey, thinly laminated dolomite, dolomite breccia, ferruginous sandstone, and arenite, and followed by 20 m of dolomite with microbial laminae. The latter is a distinct facies, which may be part of the Sweetwaters Well Member (see below).

The Yelma Formation was deposited in a fluvial to coastal setting, with carbonates of the Sweetwaters Well Member developing in a saline coastal-lagoonal environment. The Formation is interpreted as recording a marine transgression over the Yilgarn Craton and Yerrida Basin. Sedimentary structures suggest a shallow-water to partly emergent, fluvial to nearshore marine depositional environment, which was locally evaporitic at the base of the Formation. Rocks in the upper part of the Yelma Formation indicate a quiet lagoonal environment, developed behind a carbonate bank, represented by the Sweetwaters Well Member. Detrital zircon populations are dominantly 2.6–2.7 Ga in age, with a smaller c. 2.2 Ga population and minor c. 2.0 Ga population, which suggests the Yilgarn Craton and southern Gascoyne Complex were important sediment sources during basin development (Halilovic et al., 2004).

Sweetwaters Well Member

The Sweetwaters Well Member is about 100 m thick and consists mainly of light-grey to grey, massive to algal, laminated dolomite (commonly with stromatolite forms), with sandy dolomite and dolomitic feldspathic sandstone beds at top and bottom of the dolomitic succession. The dolomitic feldspathic sandstone unit at the top of the Member grades eastward to a micaceous sandstone and is overlain by granular iron formation rocks of the Frere Formation. The lower contact of the Sweetwaters Well Member is marked by about 15 m of transitional interbedded sandstone and dolomite that passes upward to a sandy and feldspathic dolomite unit. The latter contains quartz, microcline, albite, chert, and micritic dolomite embedded in a coarse-grained dolomite cement.

The Sweetwaters Well Member was intersected in a number of drillholes sunk through the Frere Formation by Renison Goldfields Ltd (Dörling, 1998a–d; Fig. 6). Samples of stromatolitic dolomite collected from drillcore show two phases or domains of dolomite; the first an aggregate of coarse-grained dolomite crystals, the other microcrystalline (micritic) and associated with microbial laminae. The coarse-grained dolomite has intergranular microcrystalline quartz and sericite. In some cases micritic dolomite forms peloids that are cemented by chalcedonic quartz. Locally, the carbonate material is replaced by cryptocrystalline quartz (chert) and chalcedonic quartz.

Scattered outcrops of Sweetwaters Well Member, along the southern shore of Lake Nabberu, about 9 km east-northeast of Horse Bore, are generally chertified, except for an area along a small tributary (MGA 272359E 7145365N) where there are good exposures of subhorizontal stromatolitic dolomite. Here, the dolomite exhibits fine microbial laminae and includes the stromatolites *Murzuna Nabberuensis, Omachtenia teagiana,* and *Asperia digitata;* Grey 1984, 1994). Drillcore sections indicate that stromatolites are generally present in metre-scale upward-shallowing cycles. They include *Asperia digitata*, which is believed to have grown in restricted, quiet-water environment, possibly supratidal ponds; *Pilbaria deverella* (Grey, 1984) indicative of moderately high-energy, lagoonal conditions; and *Ephyaltes edingunnensis* (Grey, 1994), which formed in deeper quiet water, and *Murgurra nabberuensis* (Grey, 1984) which colonized moderate energy patch reefs. Details of stromatolite taxa of the Earaheedy Basin can be found in Grey (1984, 1994). Grey (1994) suggested that these stromatolite forms are indicative of an upward-shallowing, lagoon to supratidal environment.

Magellan non-sulfide lead deposit

The large stratabound Magellan lead deposit (Fig. 7), located approximately 30 km from the town of Wiluna, is hosted in outliers of the Earaheedy Group on the southeast Yerrida Basin. The mineralization is accompanied by silicification and argillic and sericitic alteration of the host sandstone and stromatolitic dolomite of the Yelma Formation and occurs close to, or at the unconformity with the underlying Maraloou Formation (Yerrida Basin; Pirajno et al., 1998, 2004; Pirajno, 2004). Magellan is an unusual mineral deposit, first described by McQuitty and Pascoe (1998). Its discovery was announced by Renison Goldfields Consolidated in 1993, with resources estimated at approximately 220 Mt at 2.2% lead. A feasibility study of the Magellan prospects was completed in 2001 by Ivernia West Inc., with proven and probable ore reserves totalling 8.5×10^6 tonnes at 7.12% Pb (data obtained from <http://www.ivernia.com/operate/magellan htm>; no longer operating; see <www.ivernia.com> current at October 2008). Later estimates give measured and indicated resources of 21.4 Mt grading 5.8% Pb, and inferred resources of 7.2 Mt grading 4.6% Pb (SEG Newsletter, 2006). A schematic longitudinal-section of the deposit is shown in Figure 8. The Magellan deposit is exploited from two open pits, Magellan and Cano (Fig. 9), with a third pit, Pinzon, being planned. Tables 1 and 2 show inferred, indicated, and measured mineral resources and ore reserves as at 1 January 2007 (data obtained from <http://www.ivernia.com/magellan/reserves.html>, last accessed 12/04/2008).

Mining at Magellan mine is straightforward as the orebody is near the surface and has a high aspect ratio (Fig. 8).

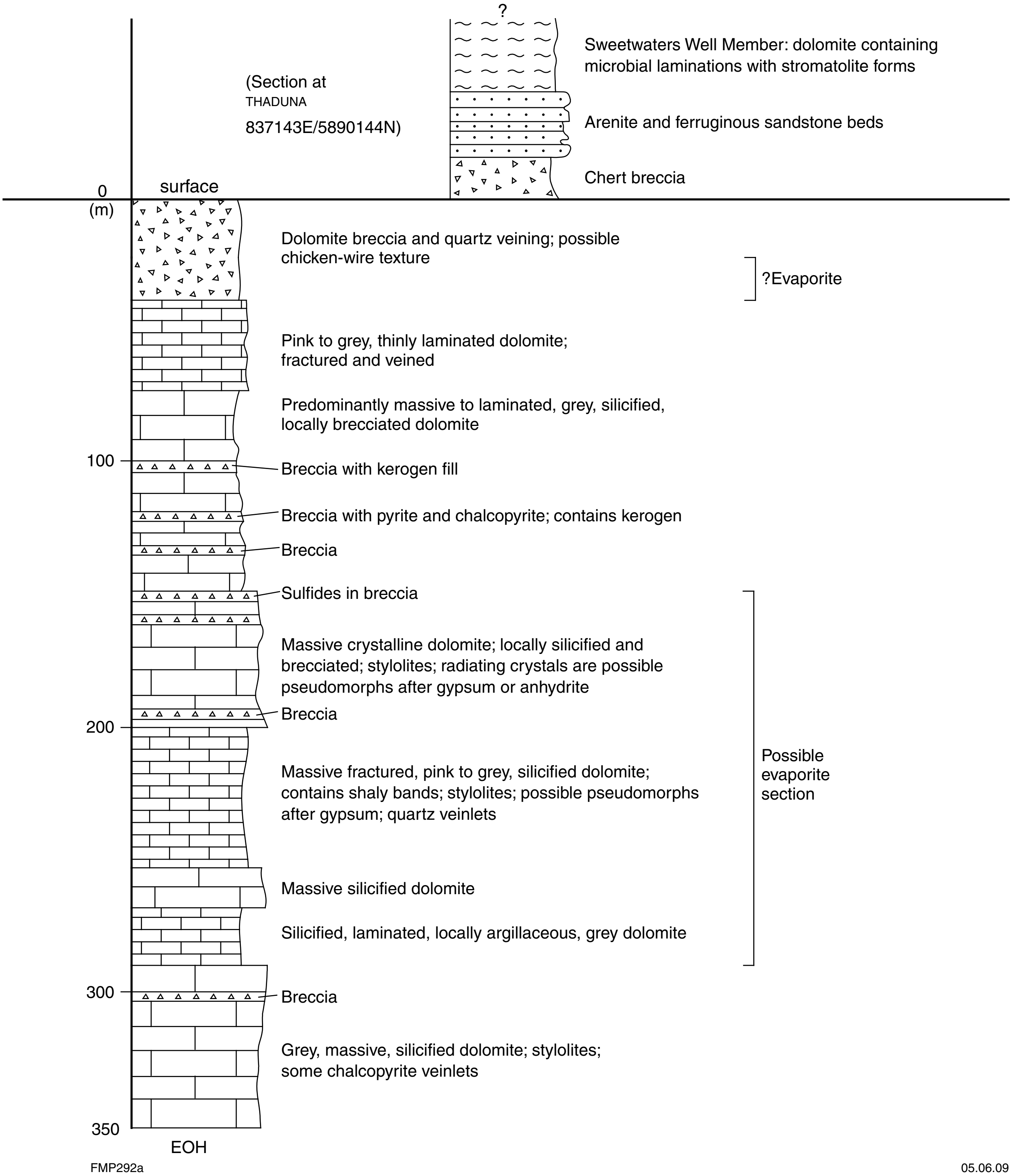

Figure 5. Composite stratigraphy of the lower part of the Yelma Formation, derived from drillcore and outcrops near Lake Gregory (width of column reflects relative resistance to weathering); after Pirajno and Adamides (2000).

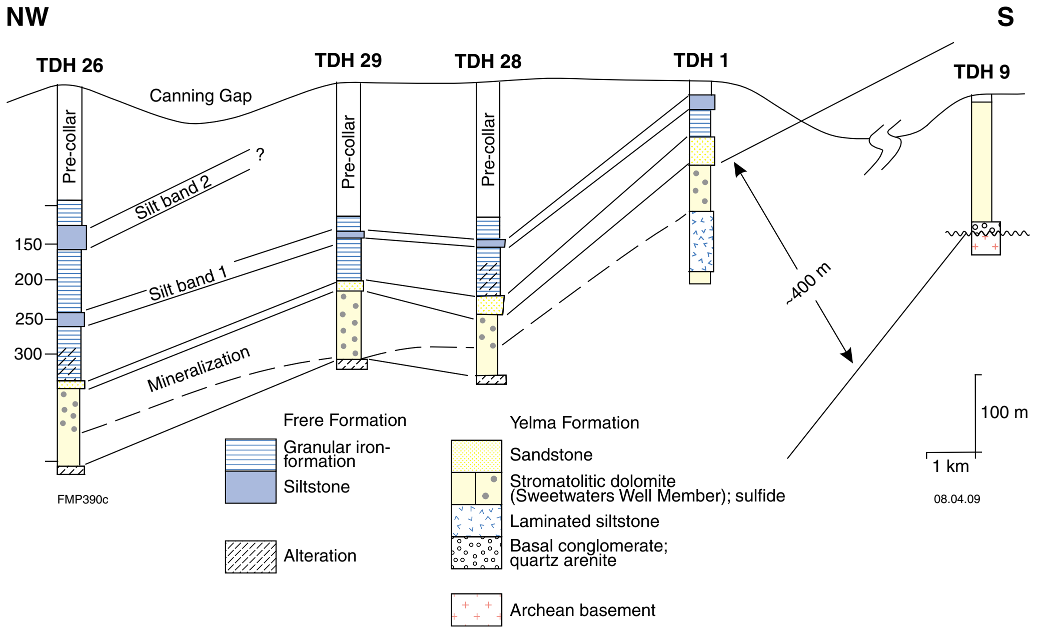

Figure 6. Schematic cross-section across drillholes in the southern margin of the Earaheedy Basin (see Fig. 4) that intersected MVT sulfide mineralization in the Sweetwaters Well Member.

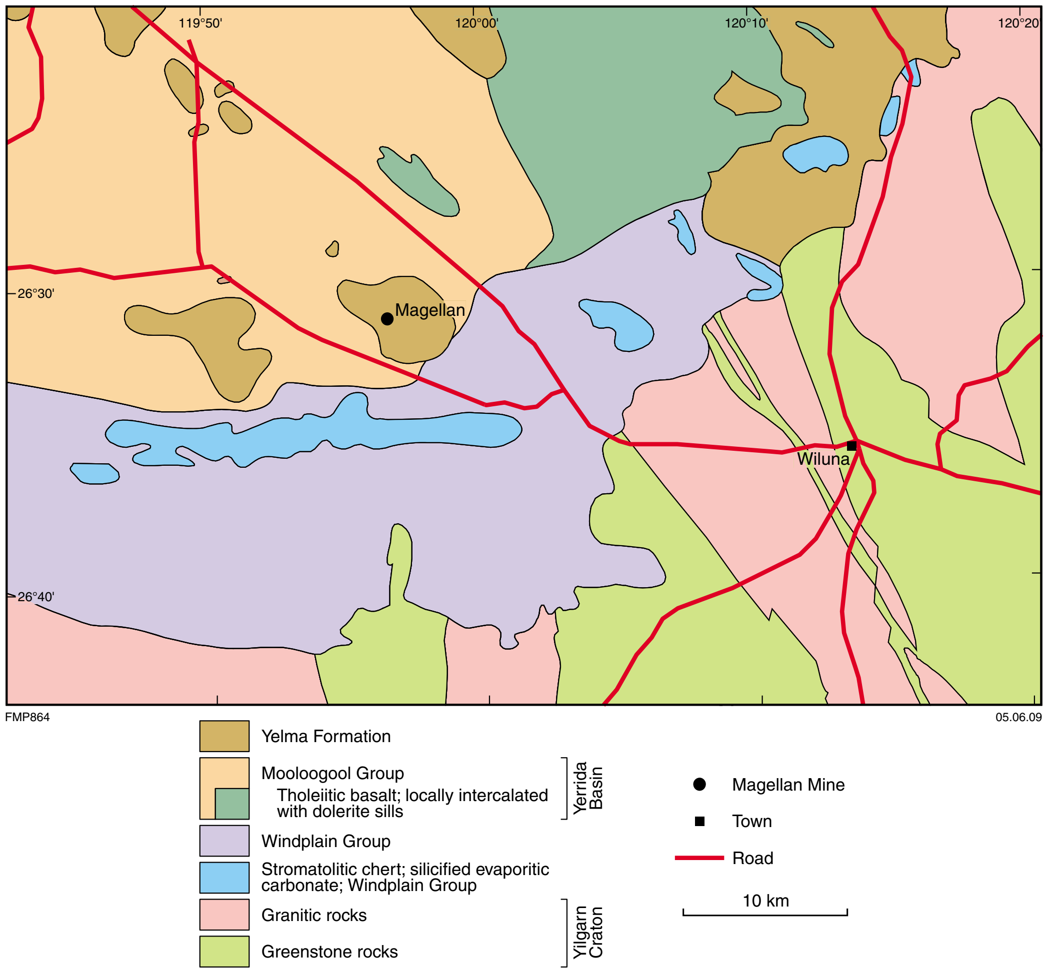

Figure 7. Schematic geological map of the southeastern part of the Yerida Basin, showing outliers of Yelma Formation and position of the Magellan deposit; after <http://www.ivernia.com/operate/magellan.htm>.

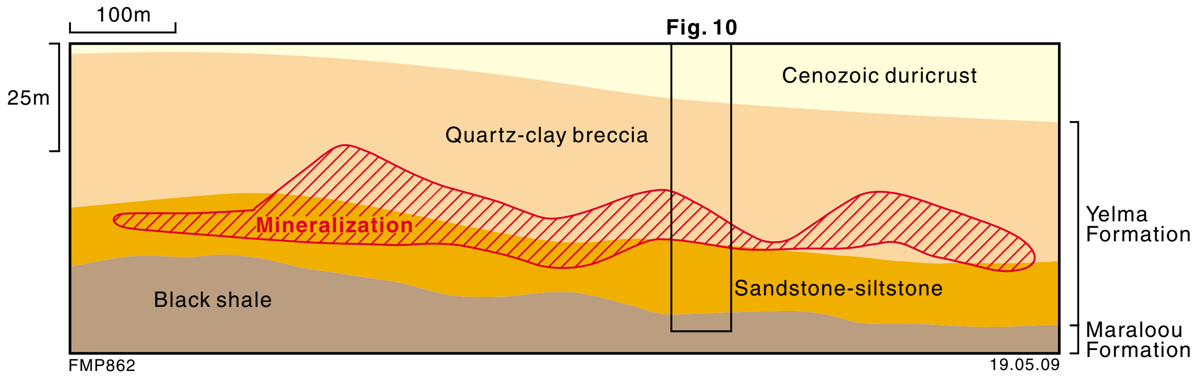

Figure 8. Schematic longitudinal section of the Magellan ore-zone in the Magellan open pit; after <http://www.ivernia.com/operate/magellan.htm>; note high aspect ratio of the ore zone.

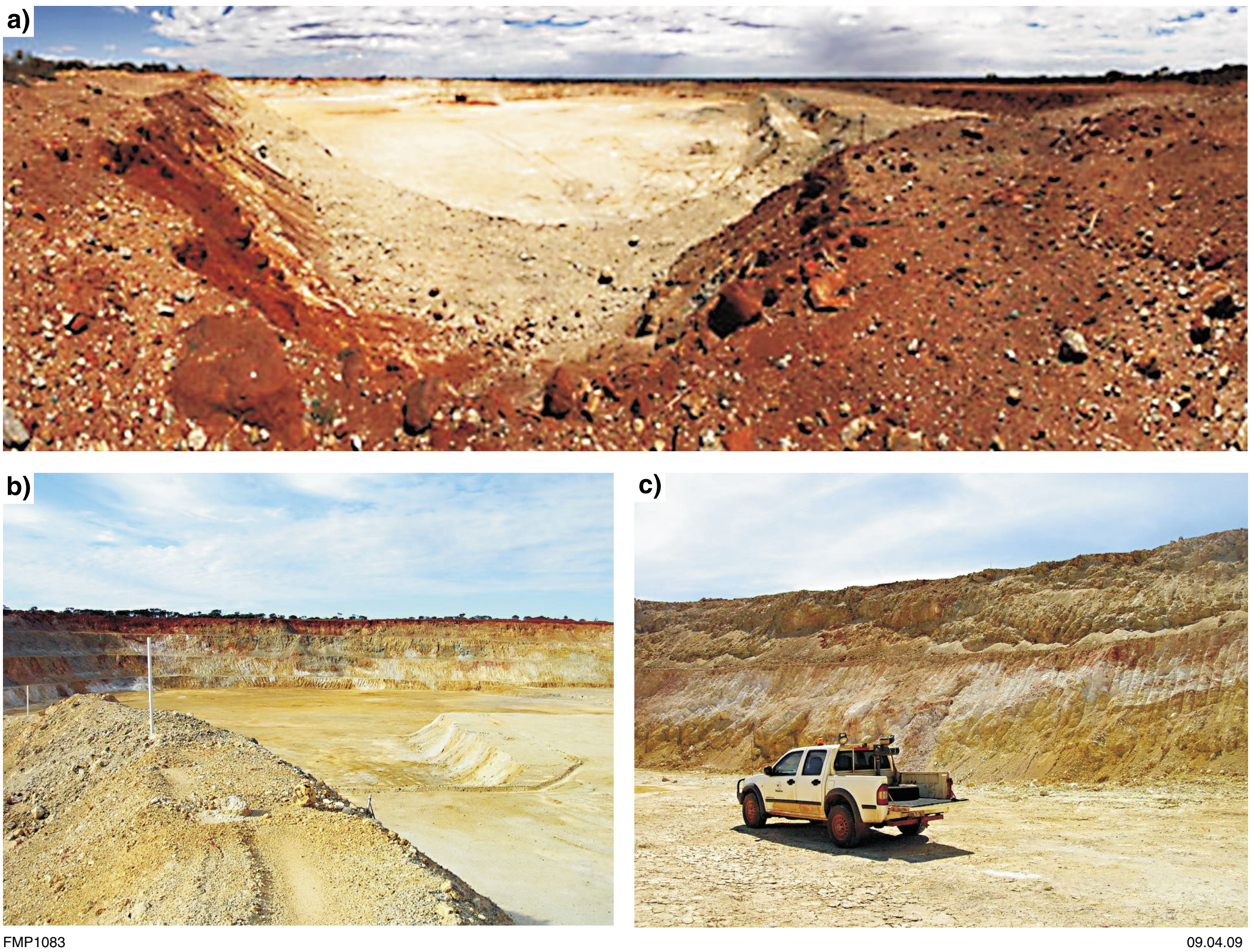

Figure 9. Field photographs of the Magellan pit (a and b) and Cano pit (c).

Table 1. Mineral resources, as at 1 January 2007; @ 3.5% Pb cut-off

	Magellan		*Cano*		*Pinzon*	
	Mt	*Pb%*	*Mt*	*Pb%*	*Mt*	*Pb%*
Measured	5.1	7.3	1.1	6.8	–	–
Indicated	3.9	5.8	0.6	6.2	3.4	6.2
Total	9.0	6.6	1.7	6.6	3.4	6.2
Inferred	2.3	5.6	0.1	5.2	0.7	5.1

Table 2. Ore reserves, as at 1 January 2007, @ 3.2% Pb cut-off

	Magellan		*Cano*		*Pinzon*	
	Mt	*Pb%*	*Mt*	*Pb%*	*Mt*	*Pb%*
Proven	4.6	7.4	1.1	6.4	–	–
Probable	1.2	6.9	0.5	6.2	2.1	6.8
Total	5.8	7.3	1.6	6.3	2.1	6.8

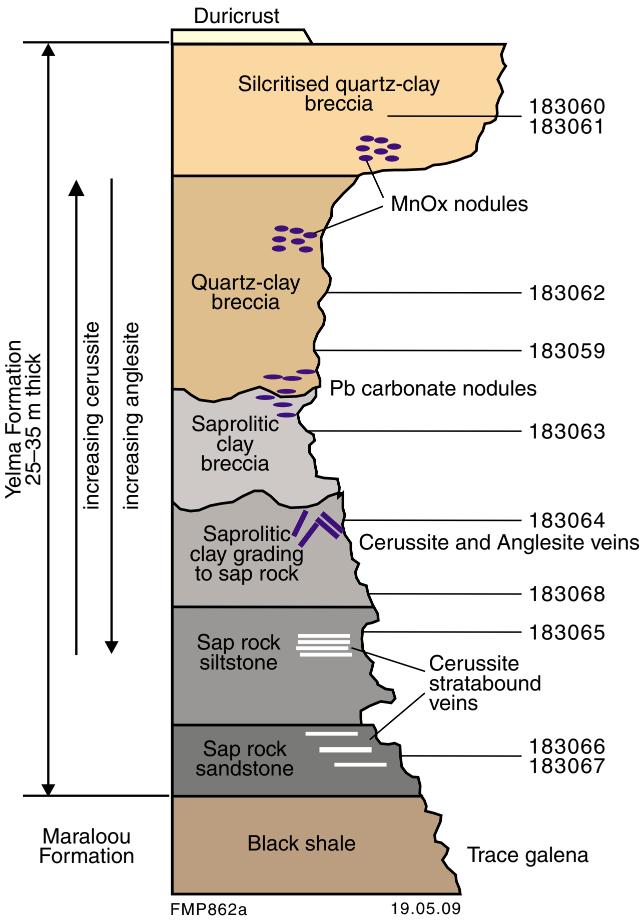

Figure 10. Schematic stratigraphic column of the Yelma Formation in the Cano open pit and position of petrographic samples; original drawing by R Burlow (unpublished).

Magellan is an open pit mining operation with a low strip ratio of approximately 2.5:1 and maximum depth of 55 m. Recovery of lead concentrates from the clean oxidized lead ore is equally simple. Ore is processed on-site through a process of conventional crushing, milling, sulfidization, and flotation concentration. The Magellan mine has been on temporary care and maintenance since April 2007 as the company seeks approval to export through the Port of Fremantle using its sealed shipment process.

Mine stratigraphy

The mine stratigraphy, from top to bottom and with informal lithostratigraphic names, established by Dörling (2006) is discussed below and shown in Figure 10.

Laterite cap: this surface unit is from 0.5 to 3 m thick, consists of variably cemented, pisolitic, clayey, red-brown lateritic material and contains nodular fragments from 2 to 15 mm in diameter as well as lithic fragments. An uneven colluvial cover is also present across much of the mine area.

Clay-quartz breccia: this unit is silicified (silcretized) in its upper parts and consists of angular to subangular clasts of chalcedonic and opaline silica supported in a matrix of clay (Fig. 11a,b). The silcretized breccia is highly variable in nature and is generally friable and contains quartz particles ranging from 0.5 to 200 mm. Dörling (2006) also reported the presence of 'cobble-sized clasts of metamorphic origin'. These 2–15 cm well-rounded clasts are composed of foliated quartzite and monzogranite, probably sourced from reworked sediments or directly from the eroded Archean terrain to the south of the Yerrida Basin. Deeper portions of the clay-quartz breccia display reduced silicification and are more clay-rich. The clay-quartz breccia is light grey to white in colour and is locally overprinted by hematitic bands that give it a mottled appearance. These bands can develop into ferruginous bands that cut across the stratigraphy and can be up to several metres wide. Vugs and cavities are common. The contact with the underlying unit is irregular, marked by a narrow oxidation zone, and dips to the northeast in the Magellan and Cano pits. This feature may mark a disconformity with the sedimentary beds below, although no definite evidence for this has been found. In high-grade ore zones, the breccia contains Pb carbonate concretions up to 300 mm across and weighing up to 4.5 kg. Manganese oxide nodules are locally present and are more prevalent in the upper bleached and depleted zones of the breccia. Although stromatolitic fragments are common, whole preserved stromatolites are rare. One 15 cm conical specimen was recovered from the Magellan pit and has a Pb carbonate mineralized core, whereas fragments of a silicified bioherm-like structure containing small unidentified columnar stromatolitic forms (*?Yelma digitata*) have also been observed. The breccia unit is interpreted as the highly altered and weathered Sweetwaters Well Member (Yelma Formation). Outcrops of relatively unaltered stromatolitic dolomite are present around the margins of the Yelma Formation outlier, where Magellan is located, and these are tentatively identified as belonging to the Sweetwaters Well Member.

Saprolitic clay zone: Underlying the breccia unit, a soft grey-white to tan-brown clay (probably with dominant

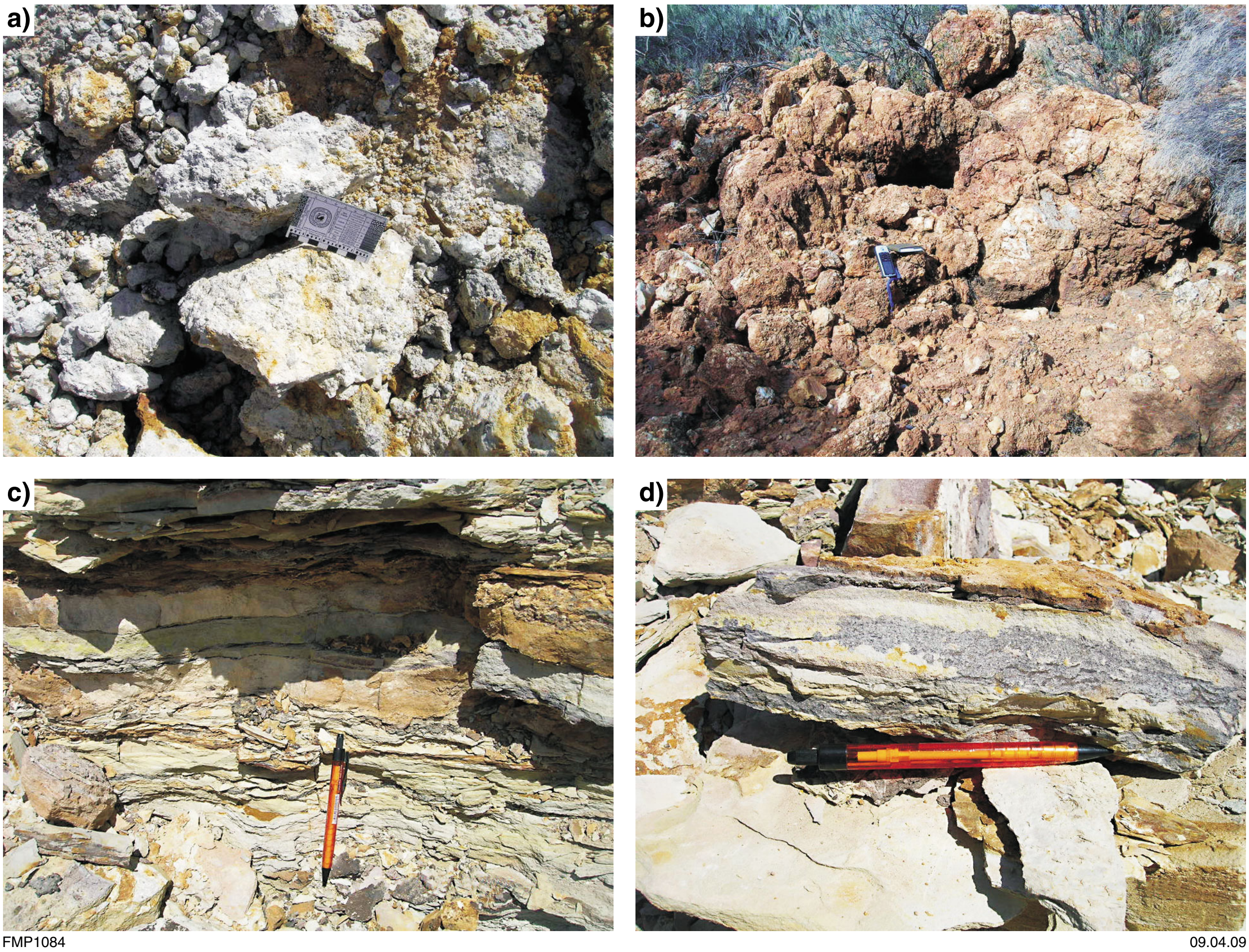

Figure 11. Field photographs of (a) quartz-clay breccia outcrop, (b) silicified chert breccia, (c) siltstone of the Yelma Formation mineralized with pyromorphite (greenish mineral) and (d) fine-grained cerussite mineralization, replacing siltstone along a fracture.

kaolinite) material is characterized by the absence of silica clasts, locally grading downward to saprock. At the top and along the margin with the quartz-clay breccia are nodules and lenses of Pb carbonate. This unit rarely displays sharp or consistent contacts with the breccia above or the sedimentary rocks below. It may represent an intraformational sediment or rip-up breccia derived from partly lithified Yelma and Maraloou Formation material.

Saprock siltstone and sandstone: This comprises partly oxidized fine- to medium-grained sandstone, interbedded with siltstone and is part of the basal Yelma Formation sequence. It is best exposed in the Cano Pit, where a rhythmic succession is observed. The sandstone shows trough and trough-cross laminations and mud cracks are locally recognizable, suggesting a very shallow to emergent depositional environment. Some blue-grey feldspathic sandstone units show moderate carbonate spotting. The sandstone and siltstone display a shallow 0–15° northerly dip with gentle interference folding about axes trending NW and NE. Ripple marks orientations from the Cano Pit suggest a general NW–SE paleocurrent trend. Stratabound zones and veins of anglesite and cerussite are up to 10 mm thick, appear to replace beds and laminae, and lead to block grades in excess of 12.8% Pb (Fig. 11c,d). More intense folding is seen locally in the southwest portion of the Cano Pit, and is possibly due to the presence of a nearby north-northwesterly trending fault.

Maraloou Formation: The Maraloou Formation surrounds the Magellan outlier, forming a low-lying plain with outcrop largely obscured by colluvium and scree material. The unit is known primarily from drill intersections beneath the Yelma Formation outlier that contains the Magellan deposit and is present within the mine area as finely laminated and fissile, black graphitic shale and shaly siltstone. It contains abundant disseminated framboidal and euhedral pyrite. In places there are traces of galena; however no economic mineralization extends into this unit.

Ore minerals

Samples taken from outcrops and open pits were examined by conventional optical microscopy and analysed by X-ray Diffraction (XRD) at the Chemistry Centre of the Department of Industry and Resources and at CSIRO in Perth. The XRD analyses were performed using a Bruker-AXS D4 XRD with copper radiation at 40 kV and 30 mA, over a range of 1.3° to 90°θ, with a 0.02° step and a 1 second per step count time. A graphite monochromators was used in the diffracted beam. The search/match was carried out with the aid of the Bruker Diffrac*plus* Search/Match software and the ICDD PDF-2 database. The quantitative phase analysis was performed using the Siroquant v. 3 software (Moulds, 2006).

The petrographic and XRD analyses show that the ore minerals are: cerrusite ($PbCO_3$), anglesite ($PbSO_4$), plattnerite (PbO_2), coronadite ($PbMn_8O_{16}$), pyromorphite ($Pb_5(PO_4)_3Cl$), and plumbogummite ($PbAl_3(PO_4)_2(OH)5H_2O$). Barite was detected in one sample. Clay minerals identified by the XRD analyses include kaolinite and nontronite. Other mineral species detected include muscovite, goethite, and perhaps phlogopite. An interesting aspect, which has important bearing for modelling the ore genesis, is that the XRD analyses show an inverse relationship between cerussite and anglesite, with the latter increase in abundance with increased depth below the surface

Petrography of a selected section

Representative samples were collected from a section of the Cano pit, which provides a complete profile of the orebody and host rocks (Fig. 9). The petrography of these samples (see Fig. 10 for location of samples), is provided in Table 3 and key photomicrographs shown in Figures 12 and 13.

Table 3. Petrography of respresentative samples from the Cano pit

GSWA no.[(a)]		*Petrography notes*	*Photomicrographs*
183059	Sweetwaters Well Member dolomite	Closely packed irregular to angular carbonate grains; very little or no interstitial material; there are two types of grains; 1) fluid inclusion-rich; 2) fluid inclusions poor	Figure 12a
183060	Near surface breccia, silcritized	Angular quartz grains and chert fragments in a matrix of microcrystalline quartz; chalcedonic quartz and lesser kaolinite; open spaces filled with macro-crystalline quartz and/or chalcedony; locally abundant carbonate inclusions	Figure 12b and c
183061	Chaotic coarse breccia; variable along strike	Angular quartz and chert fragments; some chert fragments have a distinct laminated texture; open spaces filled with comb quartz with face-controlled growth zoning, outlined by fluid inclusions; chalcedonic quartz enclosing quartz crystals outline a rhombic geometry suggesting replacement of a carbonate species; brown kaolinite veinlet with fragments of an unidentified mineral (crystal shape suggests cerussite)	Figure 12d,e,f
183062	Opaline silica with Mn oxides nodules; locally mineralized	Massive opaline silica, cut by chalcedonic quartz and second generation opal veinlets; local disseminations of subrounded unidentified fragments or minerals, possibly Mn oxides nodules enclosing euhedral carbonate (?Pb) crystals	Figure 13a
183063	Quartz–cerussite and cerussite nodule within clay-rich breccia; 10–25% Pb	Extensively jigsaw-fractured monocrystalline quartz; fractures filled with clay and cerussite; cerussite intimately associated with clay. Both are paragenetically late	Figure 13b,c
183064	Siltstone, below the ore zone. Sericitized and mineralized	Finely laminated and very fine-grained (silt-size) quartz+sericite assemblage; argillite rock. Sericite-rich laminae contain porphyroblastic cerussite	Figure 13d,e
183065	Fine-grained sandstone, locally mineralized	Angular to subangular quartz grains, lesser microcline and micas, set in a cryptocrystalline quartz/chert matrix. Abundant hematitic alteration; sericitic alteration	–
183066 and 183067	Less weathered grey sandstone	Quartz and microcline grains, rounded to subrounded, cemented by fine quartz–feldspar–hematite granular matrix; selective sericitic alteration, mostly in the matrix. Sericite cross-cutting veinlet; well-sorted feldspathic hematitic sandstone	Figure 13f
183067	Grey sandstone, with white carbonate spots and film of pale green anglesite	Fine-grained; quartz and feldspar angular to subangular grains; clast-supported; fine interstitial microcrystalline quartz and feldspar with sericitic dustings	–
183068	Cerussite laminae interbedded with limonitic material	Finely laminated texture; cerussite and other carbonate (possibly dolomite) laminae intercalated with amorphous limonitic material; locally the shape of laminae suggests replacement of biostructures (?microbial)	–

NOTE: (a) Refer to Figure 10

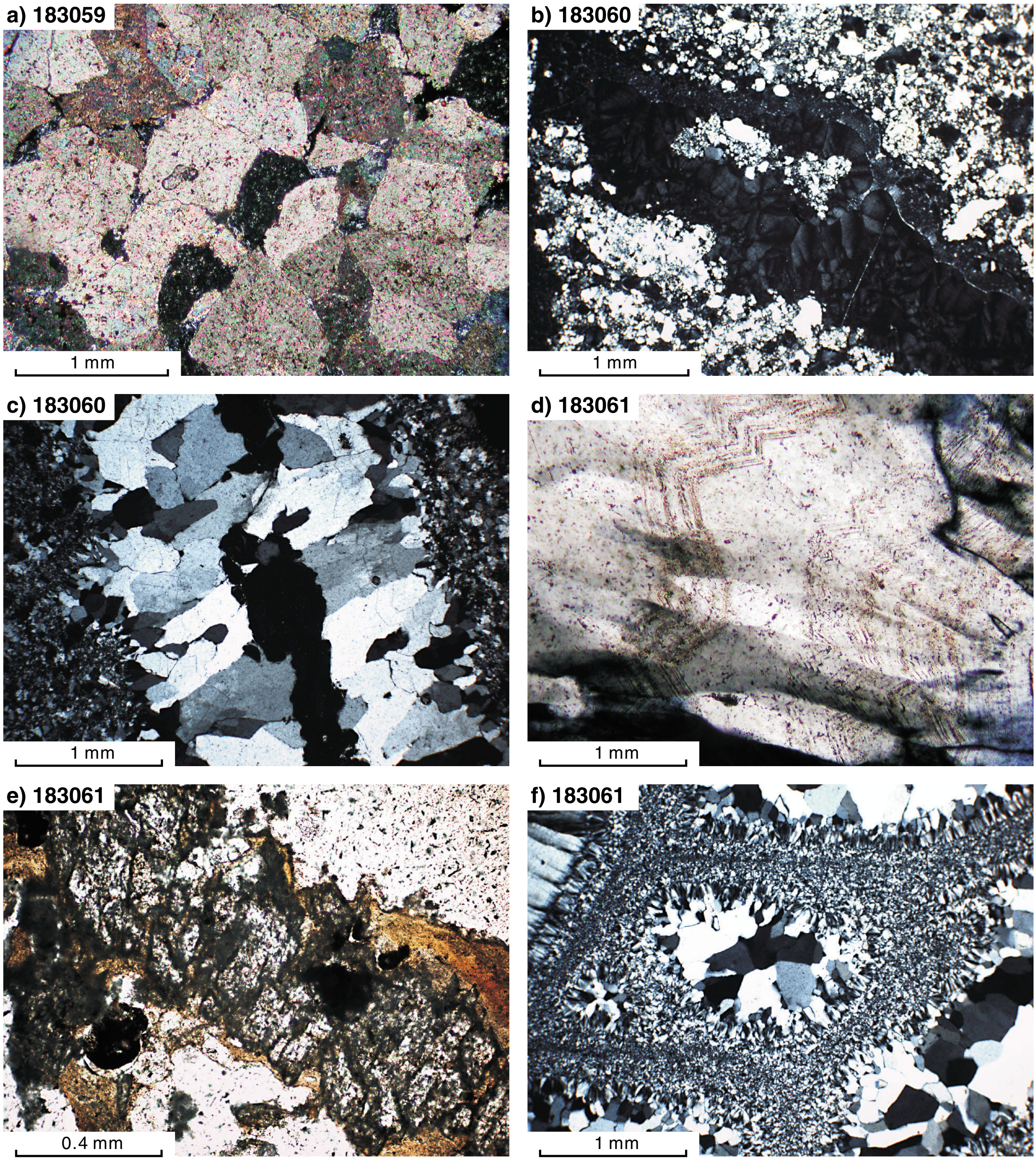

Figure 12. Photomicrographs in plane polarized light (see Table 1 for more details): a) GSWA 183059, Sweetwaters Well Member dolomite; b) GSWA 183060, kaolinite veinlet in silcritized breccia; c) GSWA 183060, vein of chalcedonic quartz and kaolinite; d) GSWA 183061, comb quartz with face-controlled zoning, outlined by fluid inclusions; e) GSWA 183061, veinlet of cerussite crystals associated with kaolinite; f) GSWA 1830161, rhombic geometry of microcrystalline quartz, probably replacing a calcite precursor. Scale bar is 1 mm.

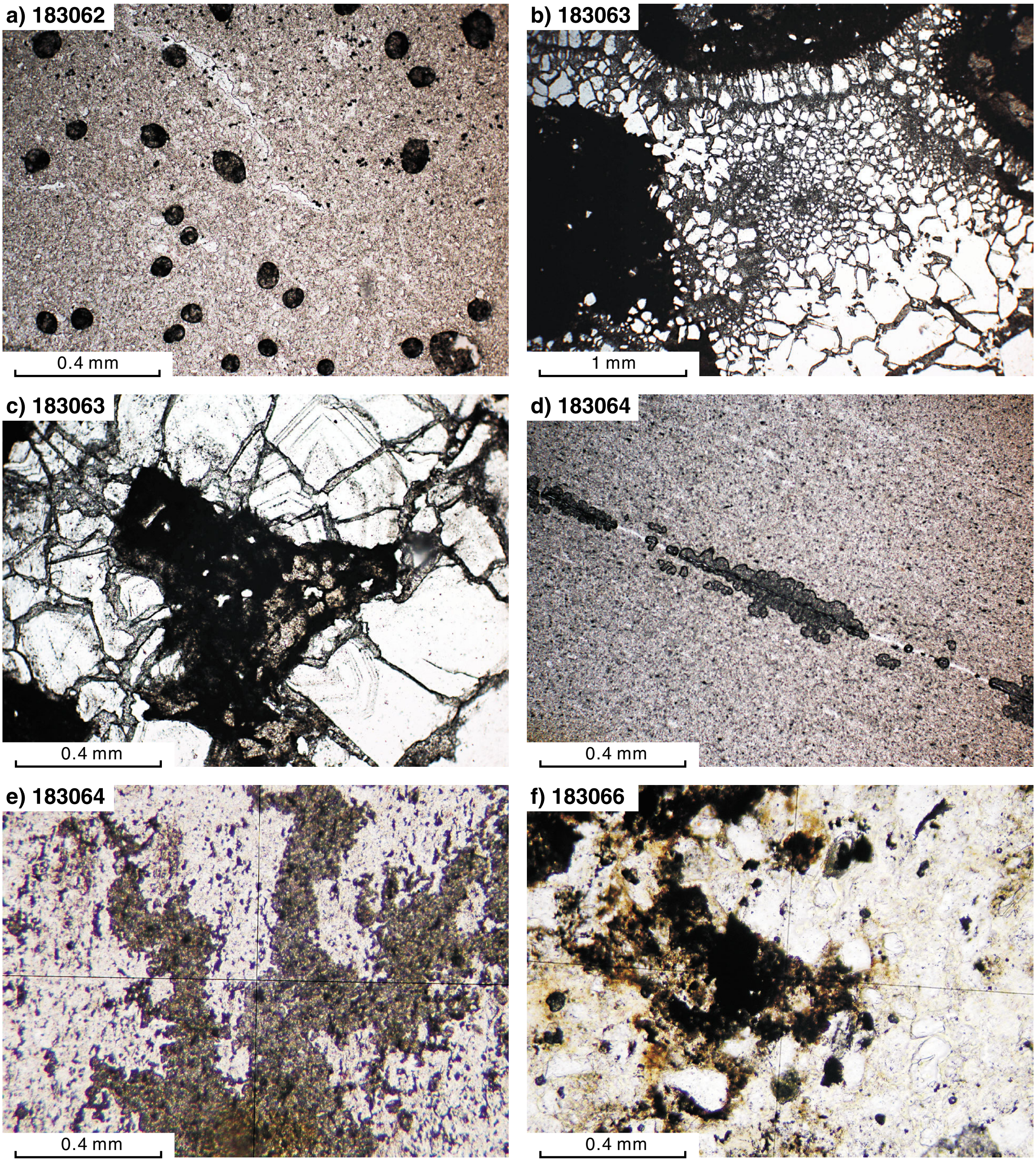

Figure 13. Photomicrographs in plane polarized light (see Table 1 for more details): a) GSWA 183062, opaline silica with small Mn-oxides nodules; b) GSWA 183063, fractured monocrystalline quartz with fractures filled by cerussite; c) GSWA 183063, zoned and fractured quartz crystals and cerussite filling the fractures; d) GSWA 183064, cerussite replacing fine-grained siltstone along a lamina (compare with Fig. 11d); e) GSWA 183064, cerussite replacing siltstone; f) GSWA 183066, quartz and K-feldspar and Fe-oxides in partly weathered fine-grained sandstone of the Yelma Formation.

Features that constrain the genesis of the Magellan non-sulfide Pb deposit

Lead minerals at Magellan are paragenetically late and tend to replace the matrix of the host rocks. Sandstone and siltstone are the dominant host rocks, characterized by selectively pervasive sericitic and kaolinitic alteration. Trace element analyses of ore materials indicate anomalous abundances of Ba (1000–1828 ppm), Mn (1900–3672 ppm), and Cu (257–400 ppm) (Pirajno and Aadamides, 2000), no sulfides are present. Homogenization temperatures of primary fluid inclusions in quartz range from 180 to 220°C, with salinities of 9–15 wt% NaCl equivalent (McQuitty and Pascoe, 1998). However, the origin of the quartz material is not specified and this could be a clast derived from an Archean quartz vein. Therefore, these homogenization and salinity measurements may not apply to the Magellan lead mineralization, as such.

The lack of sulfides at Magellan and the sole presence of oxide minerals suggest that the deposit is the result of paleoweathering processes, under physico-chemical conditions which were conducive to the oxidation and subsequent mobilization of the lead metal. The original lead was probably sourced from weathered basement rocks. This is supported by lead isotopic values ($^{206}Pb/^{204}Pb$ of 15.97153 and 15.96831; $^{207}Pb/^{204}Pb$ of 15.48658 and 15.48611; $^{208}Pb/^{204}Pb$ of 35.35561 and 35.35841), which also provided a Pb–Pb model age of c. 1.65 Ga for the the MVT sulfides (Pirajno and Adamides, 2000). This age is almost identical to the K–Ar age obtained from white micas in rocks of the Stanley Fold Belt on the northern margin of the Earaheedy Basin (Pirajno et al., in press). This is an important point, because the deformation and uplift of the northern margin of the Earaheedy Basin resulted in the formation of the Stanley Fold Belt and was probably associated with the Mangaroon Orogeny (Sheppard et al., 2005). Uplift and deformation processes in the Stanley Fold Belt would have been a major factor for the development of Mississippi Valley Type (MVT) deposits in the southern margin of the Basin (Fig. 4). Uplift of fold belts provide the topographic relief that is necessary to cause gravitational migration of basinal brines across the basin, with rates that are measured in several m/year, but that decline over a few million years as erosion progresses. Tectonically and/or gravity-driven flow in foreland basins is considered as one of the main causes for the origin of MVT mineral systems, as indeed exemplified by the carbonate-hosted Zn–Pb deposits in the Yelma Formation (Earaheedy Basin) and ultimately the Magellan non-sulfide lead deposit.

Magellan is an unusual world-class deposit containing only oxides as ore minerals, such as cerussite, anglesite, coronadite, and pyromorphite. The Pb metal and carbonate mineralization could have resulted from the intense weathering of a precursor MVT deposit, in which the sulfides were completely weathered out with removal of the more mobile elements; such as S, Fe, and Zn. The Pb might have been re-precipitated as a carbonate due to the presence of abundant Ca in the degrading carbonate rocks. If this is the case, the Magellan non-sulfide Pb deposit may be a variant of non-sulfide Zn deposits (see Hitzman et al., 2003 for a comprehensive review).

The origin of the Magellan non-sulfide Pb deposit, and nearby similar prospects (Cano, Cortez, Drake, and Pizarro) is therefore likely to be associated with the oxidation of MVT-related Zn and Pb sulfides. The oxidation of these sulfide minerals led to the progressive replacement by carbonates and oxides. The resulting supergene deposits can be of three types (Hitzman et al., 2003): direct-replacement, wall-rock replacement, or karst fill. Direct-replacement from MVT sulfides are essentially Zn-rich gossans and tend to be mineralogically simple, with mineral species such as smithsonite, hemimorphite, and hydrozincite. During supergene oxidation of sulfides abundant acid is formed to completely leach the Zn metal in the near-surface. This leaching results in the formation of jasperoidal gossans with Fe oxides and cerussite and lesser other-metal carbonates (Hitzman et al. 2003). It is in this regime that residual Pb-rich deposits, such as Magellan, can form by the complete removal of Zn. Figure 14, taken from Hitzman et al. (2003), illustrates the concept and shows the Magellan Pb deposit would classified as wall-rock replacement type (Fig. 14b). Carbonate-rich (limestone, dolomite, calcareous sandstone) rocks are needed for this type of mineralization to form due to their high reactivity. Acidic groundwaters flow downward from the original sulfide body near or exposed at the surface, permeate into and react with the calcareous wallrocks, forming a replacement non-sulfide deposit. If this model of ore genesis is correct, it may also imply that at Magellan Zn-oxides may still exist at depth. The sequence of mineral phases that develop during the progressive replacement of a MVT sulfide body, shown in Figure 14c, in which the end-products are mainly chalcedonic silica-hematite and cerussite, are observed at Magellan. The oxidation-destruction of primary sulfides provides a low pH environment and sulfate-bearing solutions that can leach and carry metals. Pyrite, marcasite, and Fe-rich sphalerite are needed to form large quantities of acid solutions. The presence of pyromorphite supports the idea of acidic solutions, as this mineral results from the action of phosphoric acid on gelana and cerussite (Dana and Ford, 1966). In some cases, it is probable that oxidation is mediated by thermophilic bacteria.

Proposed genetic model

For the Magellan non-sulfide lead deposit, a ‘top-down’ genetic model is proposed in which four stages can be considered, as shown in Figure 15 and explained below. In stage 1, the precursor sequence of carbonate rocks of the Sweetwaters Well Member, sandstone and siltstone of the basal Yelma Formation (Earaheedy Group) discomformably overly black shales of the Maraloou Formation. Stage 2 is the hydrothermal event leading to the development of MVT sulfide bodies, by gravitational flow of basinal brines from the uplifted margins of the Earaheedy Basin (Stanley Fold Belt). Mineral species of the Earaheedy MVT occurrences include pyrite, sphalerite, chalcopyrite, and galena, accompanied by weak silica and Fe-oxides alteration. Sulfide replacement of carbonate rocks takes place within the Sweetwaters Well Member,

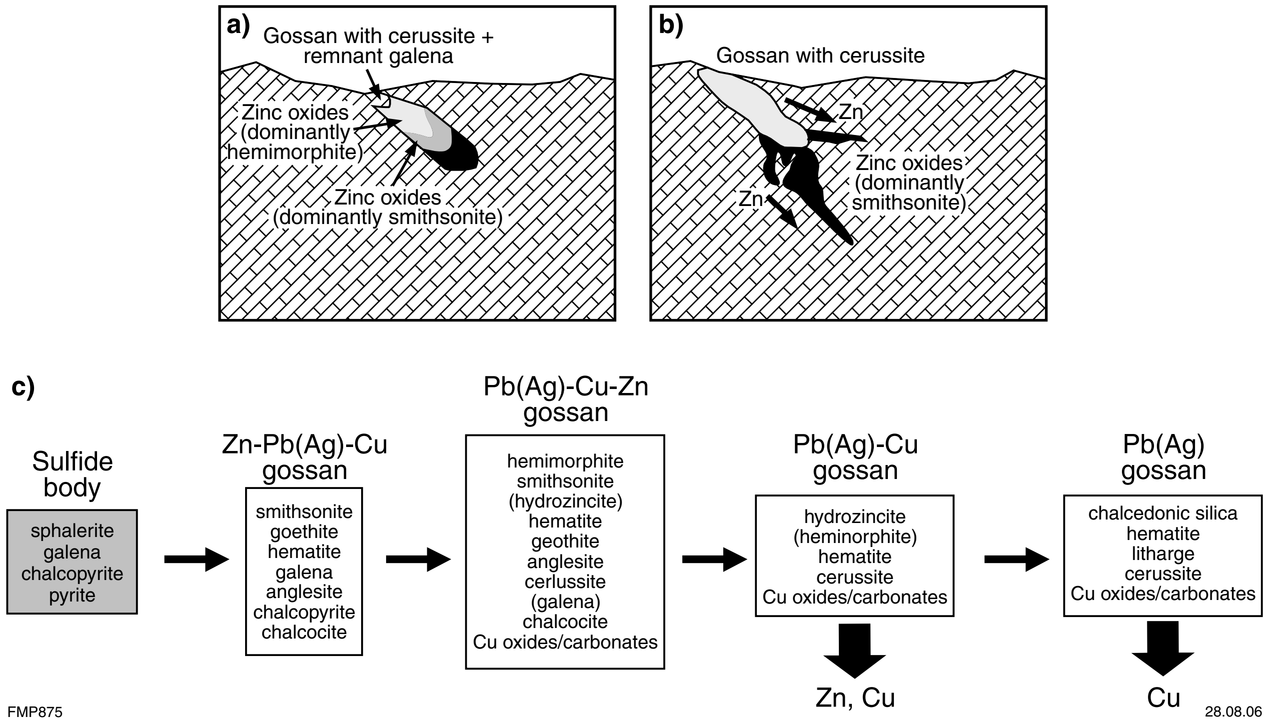

Figure 14. Genetic models for the formation of non-sulfide mineral systems: a) direct replacement type; b) wallrock replacement type (applicable to Magellan); c) mineralogical changes related to progressive replacement of sulfides; after Hitzman et al. (2003).

resulting in the formation of typical MVT stratabound sulfide bodies.

During stage 3, dissolution of carbonate during karsting processes resulted in the formation of cavities, followed by volume reduction due to collapse of the karst cavities. Stage 3 may have occurred at shallow depth, i.e. after removal of the overburden during the Permian–Carboniferous glaciation, which also brought the sequence closer to the surface and enabled meteoric water infiltration.

Wholesale oxidation of lead and zinc sulfides resulted in the flushing out of highly mobile zinc, leaving less soluble lead behind to form sulfate (anglesite), accompanied by intense silica alteration. The collapse of karst cavities, silica alteration, and formation of lead sulfate combined to form the quartz breccia. For this stage the following reactions are envisaged:

Sulfide dissolution (after zinc flushed out):

$$PbS + 4H_2O \rightarrow PbO_4 + 8H^+$$

Galena — Plattnerite

and/or

$$H_2S + 4H_2O \rightarrow H_2SO_4 + 8H^+$$

Acid leaching ensued due to the production of sulfuric acid.

Hot and wet climatic conditions resulted in intense weathering and infiltration of rain water rich in dissolved CO_2, which converted lead sulfate to lead carbonate, according to the reaction:

$$PbSO_4 + H_2O + CO_2 \rightarrow PbCO_3 + H_2SO_4$$

Anglesite — Cerussite

As the CO_2-rich meteoric waters progressively percolated downwards into the sandstone and siltstone of the Yelma Formation underlying the dissolved carbonate units of the Sweetwaters Well Member, more and more cerussite formed at the expense of anglesite and led to the formation of the Magellan ore. At the same time acid leaching by sulfuric acid induced strong kaolinization of host rocks. The timing of the climatic conditions necessary to account for this weathering is poorly constrained. Hocking et al. (2007) suggested that in the Paleocene–Eocene and Oligocene the climate in Western Australia would have been warm and wet (tropical to sub-tropical), during which time (Mid–Late Eocene) extensive silcrete and ferricrete were formed. This climatic regime could have been ideal for the formation of Magellan style mineral systems, providing that an adequate protore source was available and suitably near-surface. A hot and humid climate could have existed before the Cenozoic but, as far as is currently known, there is no geological record of these conditions in the study area.

Conclusions

The world-class Magellan non-sulfide lead deposit was probably formed by weathering and oxidation processes that acted on pre-existing MVT stratabound sulfides, hosted by the Sweetwaters Well Member of the Yelma Formation (<1.84 Ga Earaheedy Basin). The deposit is located in outliers of the Yelma Formation that overlie black shales of the Maralou Formation of the Mooloogool Group (c. 1.84 Ga upper parts of the Yerrida Basin). The mineralization comprises cerussite and lesser anglesite,

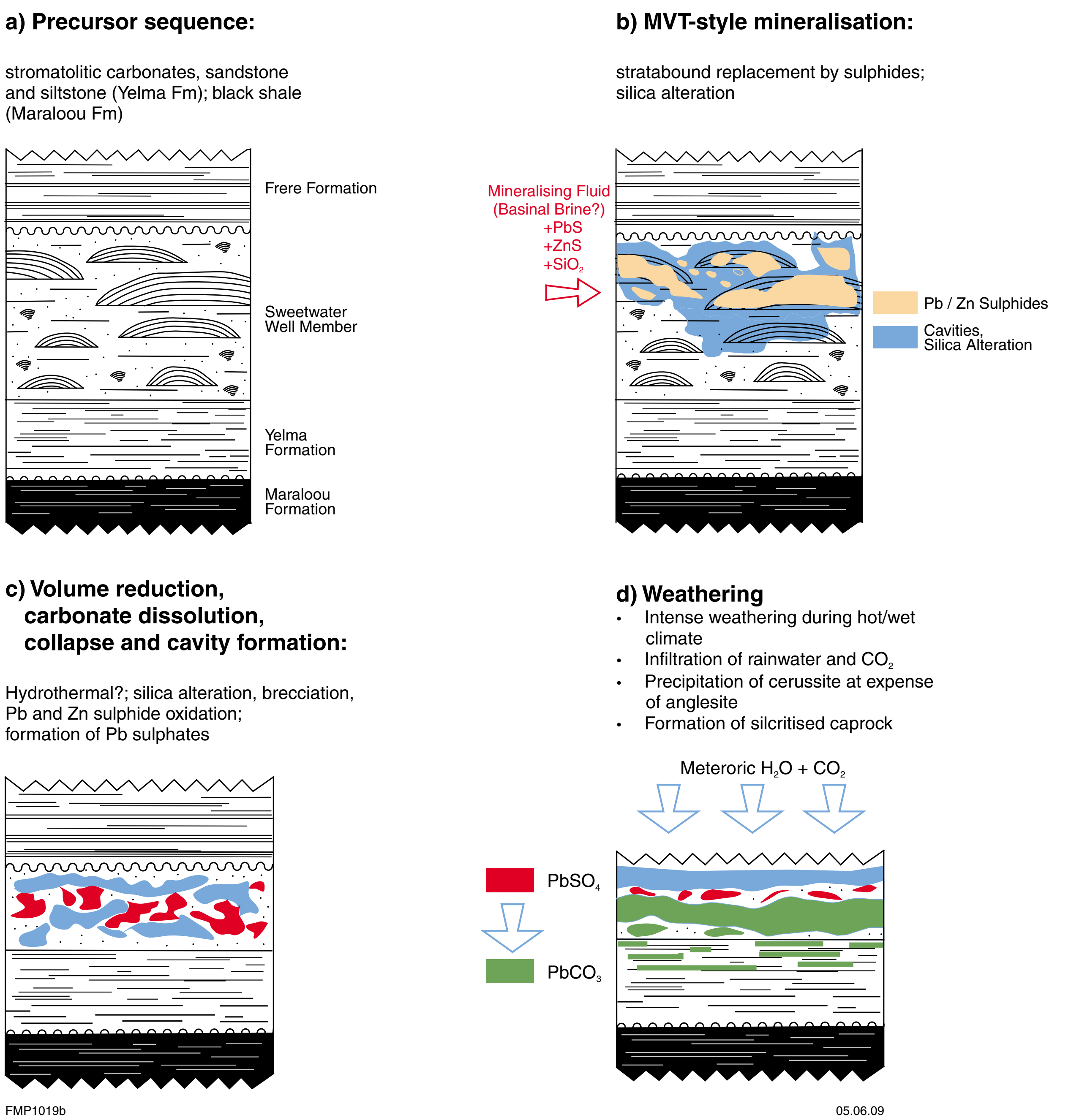

Figure 15. Four-stage genetic model for the Magellan non-sulfide lead ore; details in text.

with the latter decreasing with depth. On the basis of our current knowledge, a model of ore genesis is proposed in which lead sulfate and lead carbonate were precipitated through a series of chemical reactions that attacked carbonate rocks containing zinc and lead sulfides, which were dissolved with the host carbonate. The more mobile zinc was flushed out, with less mobile lead, which precipitated firstly as a sulfate mineral (anglesite), remaining in the host rock. Weathering in a hot and humid climate and downward migration of CO_2 rich meteoric waters, resulted in the replacement of the anglesite by lead carbonate (cerussite). The ore zone is shallow, near flat-lying, tabular, and has a high aspect ratio, which make it easy to mine by open pit methods. The ore is exploited from two open pits: Magellan and Cano, and a third pit, Pinzon, is being planned. At the time of writing the Magellan mine is on a care-and-maintenance program.

The development of a Magellan-style mineral system requires two essential conditions: pre-existing sulfide mineralization, and a hot and wet climate to induce weathering and destruction of the sulfide bodies by descending oxidizing meteoric waters. In Western Australia, any near-surface massive sulfide ores could have been the target of intense weathering and the formation of Magellan-type ore. These non-sulfide ores are difficult to recognize in the field and can be easily overlooked while searching for massive sulfide ore.

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The Magellan non-sulfide lead deposit, Yerrida and Earaheedy Basins, Western Australia

Pirajno and Burlow

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